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Abstract of a proposed presentation at workshop for
CFD Applications in Rocket Propulsion to be held at
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INCOMPRESSIBLE NAVIER-STOKES CALCULATIONS IN PUMP FLOWS

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Flow through pump components, such as the SSME-HPFTP Impeller and an advanced rocket pump impeller, is efficiently simulated by solving the incompressible Navier-Stokes equations. The solution method is based on the pseudocompressibility approach and uses an implicit-upwind differencing scheme together with the Gauss-Seidel line relaxation method. The equations are solved in steadily rotating reference frames and the centrifugal force and the Coriolis force are added to the equation of motion. Current computations use one-equation Baldwin-Barth turbulence model which is derived from a simplified form of the standard $k - \epsilon$ model equations. The resulting computer code is applied to the flow analysis inside an 11-inch SSME High Pressure Fuel Turbopump impeller, and an advanced rocket pump impeller. Numerical results of SSME-HPFTP impeller flow are compared with experimental measuremnts. In the advanced pump impeller, the effects of exit and shroud cavities are investigated. Flow analyses at design conditions will be presented.

INCOMPRESSIBLE NAVIER-STOKES COMPUTATIONS IN PUMP FLOWS

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Workshop for CFD Applications in Rocket Propulsion
NASA-MSFC, April 20-22, 1993

Outline

- Introduction
- Method of Solution
- Previous Work
- SSME-HPFTP Impeller Results
- Advanced Pump Impeller Analysis
- Summary

Introduction

- Motivation
  - ≫ Increase efficiency and reliability of the pump components in advance liquid rocket engine.
- Objective
  - ≫ To enhance, and validate a computational procedure for pump flow analysis.
- Approach
  - ≫ CFD validation cases parallel to experimental studies (MSFC Pump Consortium Team)
  - ≫ Component analysis in steadily rotating frames
  - ≫ 3-D viscous incompressible flow solver (INS3D-UP)
  - ≫ One-equation Baldwin-Barth turbulence model
  - ≫ Coarse/medium size grid for engineering purposes (150K - 600K).

Solution Method (INS3D-UP)

- Based on method of pseudocompressibility
- Both steady-state and time-accurate formulation
- Multi-Zone and Overlapped grid scheme capability
- Central differencing for viscous fluxes
- Upwind differencing for convective fluxes
  3rd and 5th order flux-difference splitting is used for the right hand side terms
- Implicit Gauss-Seidel line relaxation scheme
- Inflow and Outflow boundaries based on Method of Characteristics
  Inflow Boundary : Three velocity components specified
  Outflow Boundary : Static pressure specified
- Quasi-implicit boundary conditions at zonal interfaces

Steady-State Formulation

- Introduce pseudocompressibility term to the continuity equation

$$\frac{\partial p}{\partial \tau} = -\beta \left(\frac{\partial \hat{U}}{\partial \xi} + \frac{\partial \hat{V}}{\partial \eta} + \frac{\partial \hat{W}}{\partial \zeta} \right)$$

$$\frac{\partial \hat{q}}{\partial \tau} = -\frac{\partial}{\partial \xi}(\hat{e} - \hat{e}_v) - \frac{\partial}{\partial \eta}(\hat{f} - \hat{f}_v) - \frac{\partial}{\partial \zeta}(\hat{g} - \hat{g}_v) + S$$

  - $\gg$ β is an pseudocompressibility constant
  - $\gg$ τ is a pseudo-time step
  - $\gg$ S is a source term for centrifugal and coriolis forces

- Euler Implicit time discretization

- Solve system of equations iteratively in pseudo-time until solution converges to a steady state

Previous Work

- Flow analysis for a high-flow-coefficient inducer was completed. The results from one-equation Baldwin-Barth turbulence model compare fairly well with the experimental data.
- Advanced impeller design was analyzed for baseline and optimized geometries. Inflow conditions were not avialable experimentally.
- Advanced impeller design was analyzed for design and off-design conditions (100, 120, 80, and 60 percent of design flows).
- The effect of downstream boundary conditions was investigated.

Recent Work

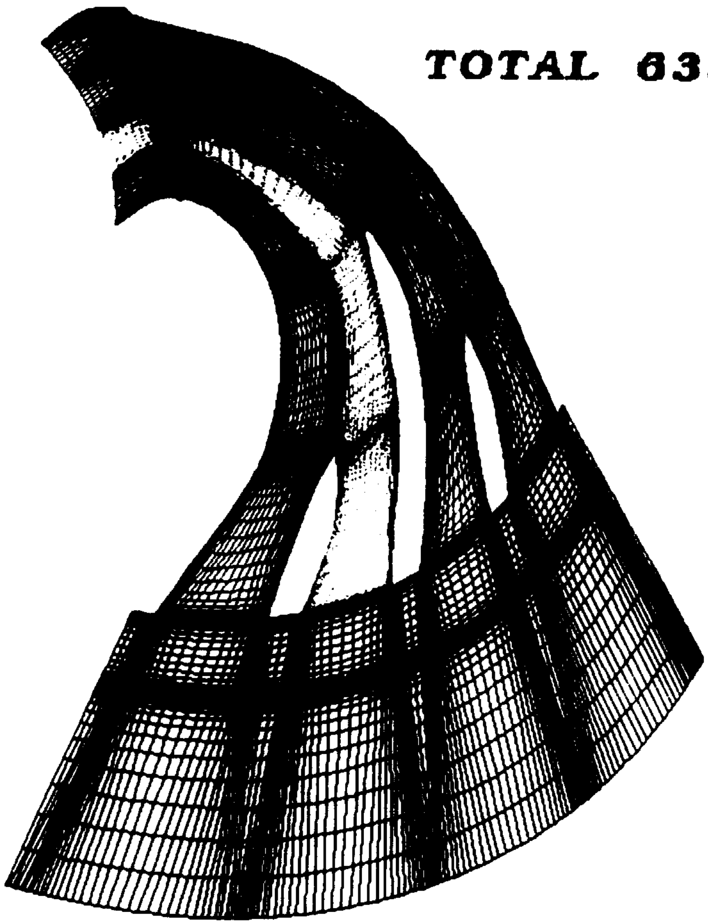
- 11 inch SSME-HPFTP impeller was analyzed. Exit cavities were included.
- Advanced impeller design was analyzed with the recent inflow conditions.
- The effect of exit cavities were investigated.
- The shroud cavity calculation is currently underway.

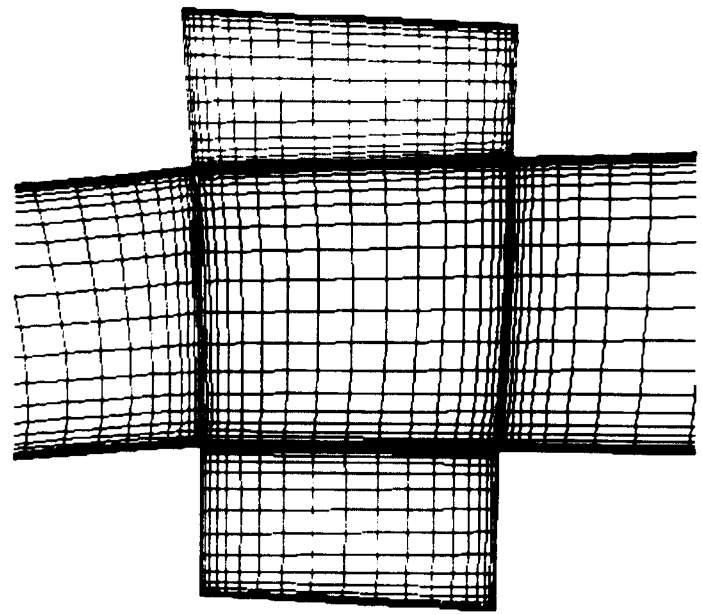
SSME-HPFTP Impeller Computations

- Grid 1 : 108 x 25 x 33
- Grid 2 : 108 x 25 x 33
- Grid 3 : 108 x 25 x 33
- Grid 4 : 108 x 25 x 33 / TOTAL : 633 K
- Grid 5 : 37 x 132 x 33
- Grid 6 : 21 x 132 x 21
- Grid 7 : 21 x 132 x 21

SSME HPFTP Impeller Grid

TOTAL 633,000 GRID POINTS

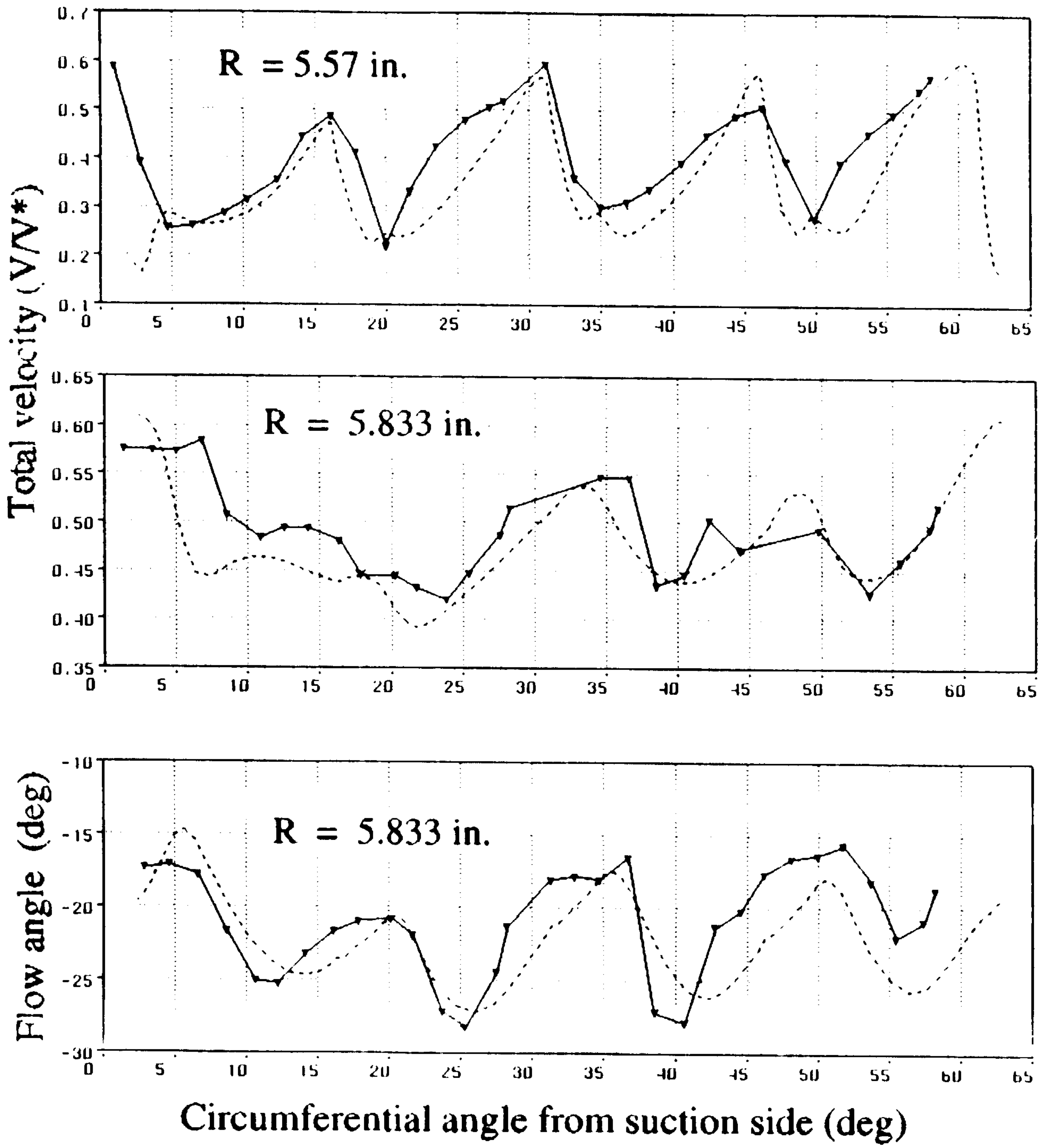




SSME-HPFTP Impeller Computations

Flow Split

- Full Blade S.S. - Short Partial P.S. : % 19.7 (comp) % 20.84 (exp)
- Short Partial S.S. - Long Partial P.S. : % 25.3 (comp) % 26.48 (exp)
- Long Partial S.S. - Short Partial P.S. : % 25.7 (comp) % 24.54 (exp)
- Short Partial S.S. - Full Blade P.S. : % 29.3 (comp) % 28.14 (exp)



SSME–HPFTP Impeller downstream of impeller exit plane (51% of blade height)

Impeller exit radius : 5.5 in.

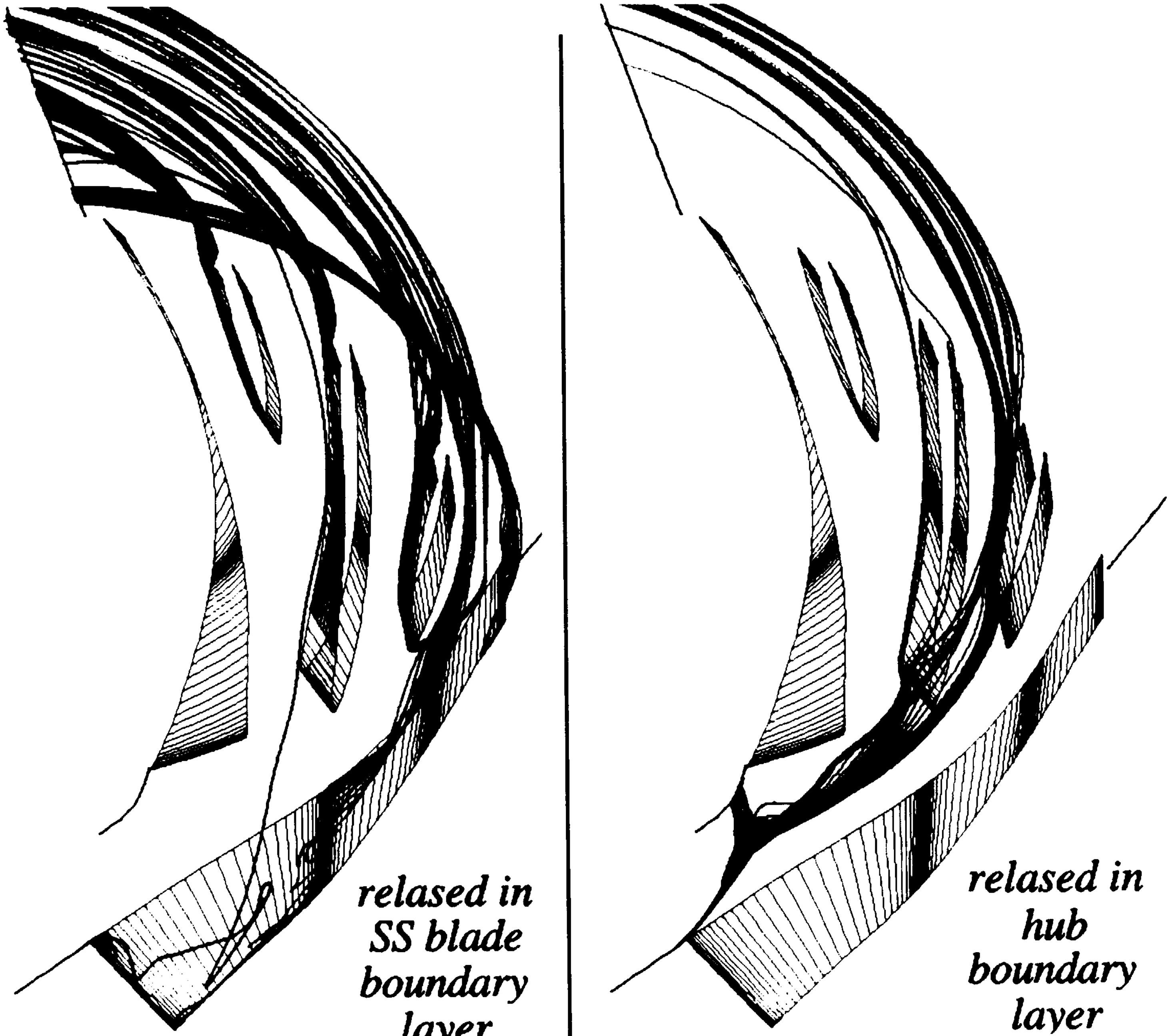
V* : Impeller exit wheel speed (303.5 ft/sec)

11 INCH SSME HPFTP IMPELLER

particle traces colored by relative total velocity magnitude

total velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000
0.70000
0.75000
0.80000
[illegible]
0.90000
0.95000
1.00000
1.05000
1.10000
1.15000
1.20000
1.25000
1.30000
1.35000
1.40000
1.45000



11 INCH SSME HPFTP IMPELLER

particle traces
colored by
relative
total
velocity
magnitude

total
velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000
0.70000
0.75000
[illegible]
[illegible]
[illegible]
0.95000
1.00000
1.05000
1.10000
1.15000
1.20000
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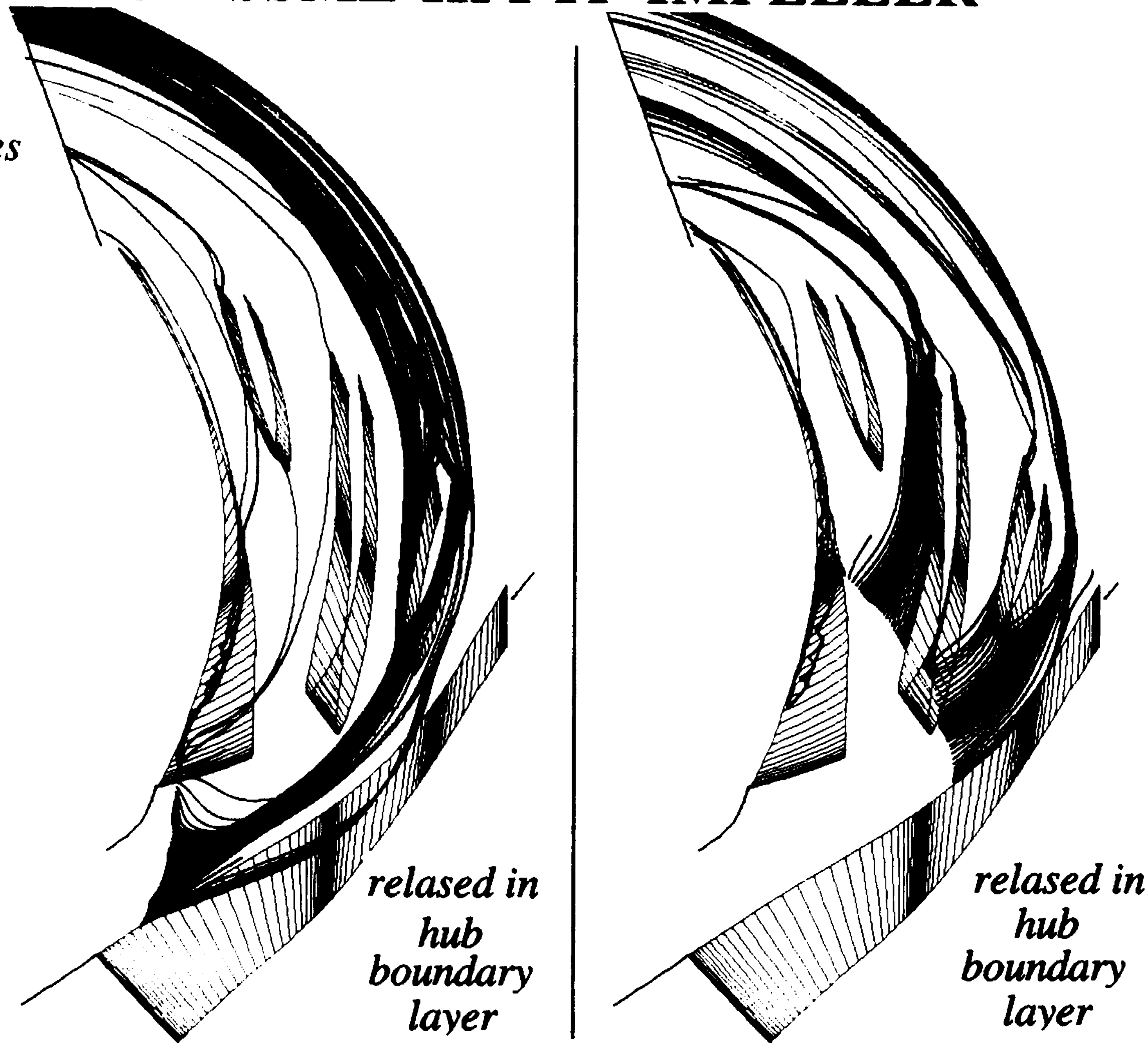
1.35000
1.40000
1.45000

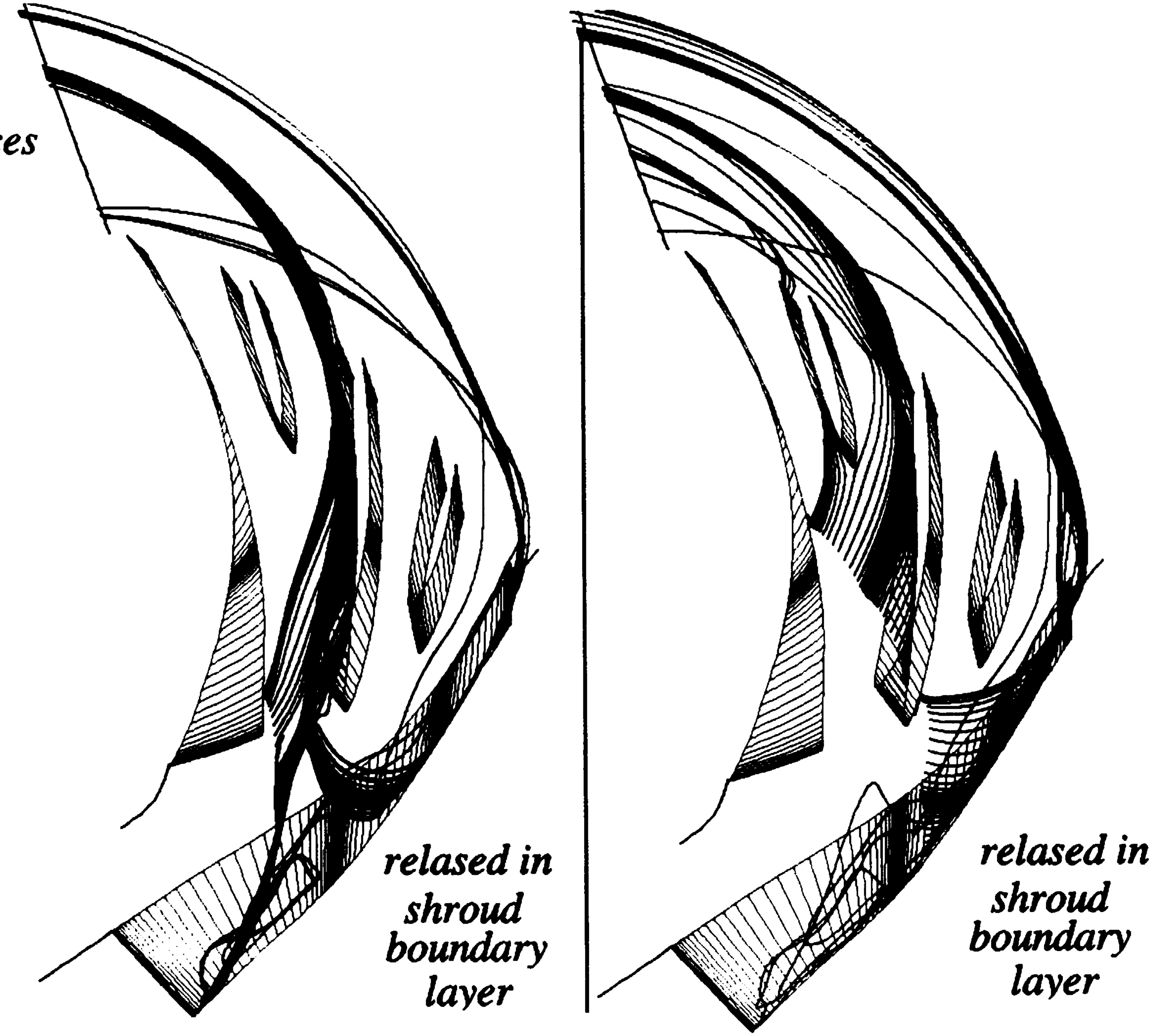


11 INCH SSME HPFTP IMPELLER

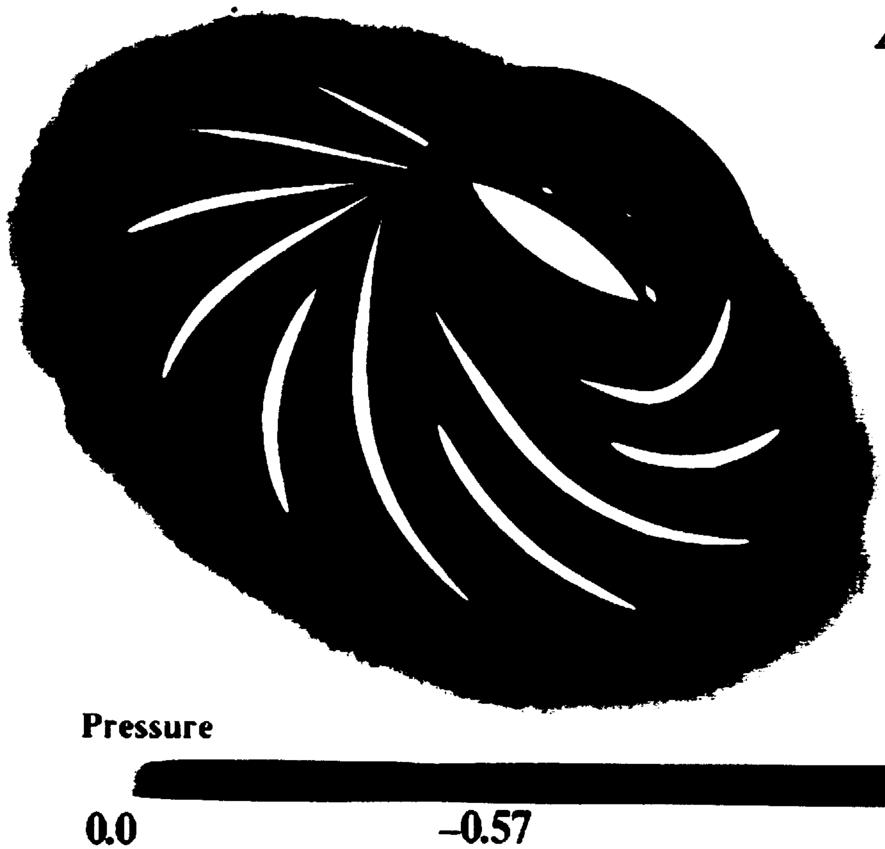
particle traces colored by relative total velocity magnitude

total velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000
0.70000
0.75000
0.80000
0.90000
0.95000
1.00000
1.05000
1.10000
1.15000
1.20000
1.25000
1.30000
1.35000
1.40000
1.45000



Advanced Rocket Pump Impeller



Shrouded impeller

6 full blades

6 partial blades

Impeller shaft speed : 6322 rpm

Impeller exit wheel speed :

249.5 ft/sec

Impeller exit diameter : 9.045 in.

Reynold Number : 1.81e+5

Reference length : 1 inch

Reference velocity : 284 in/sec

Fluid medium : water at 70 F

Baseline Impeller

Case 1 – No cavities (slip downstream b.c.)

Case 2 – Exit cavities

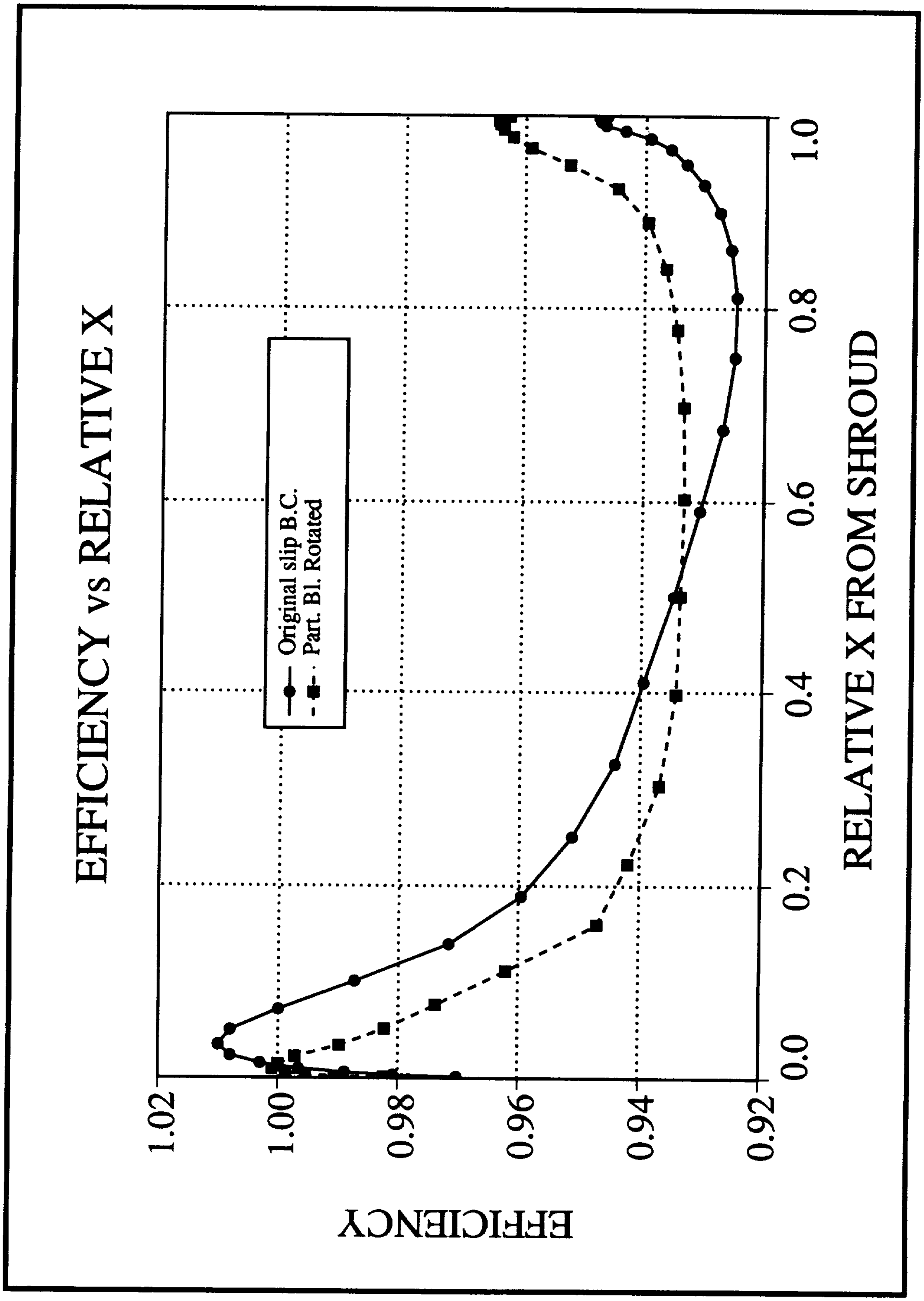
Case 3 – Exit cavities + shroud cavity

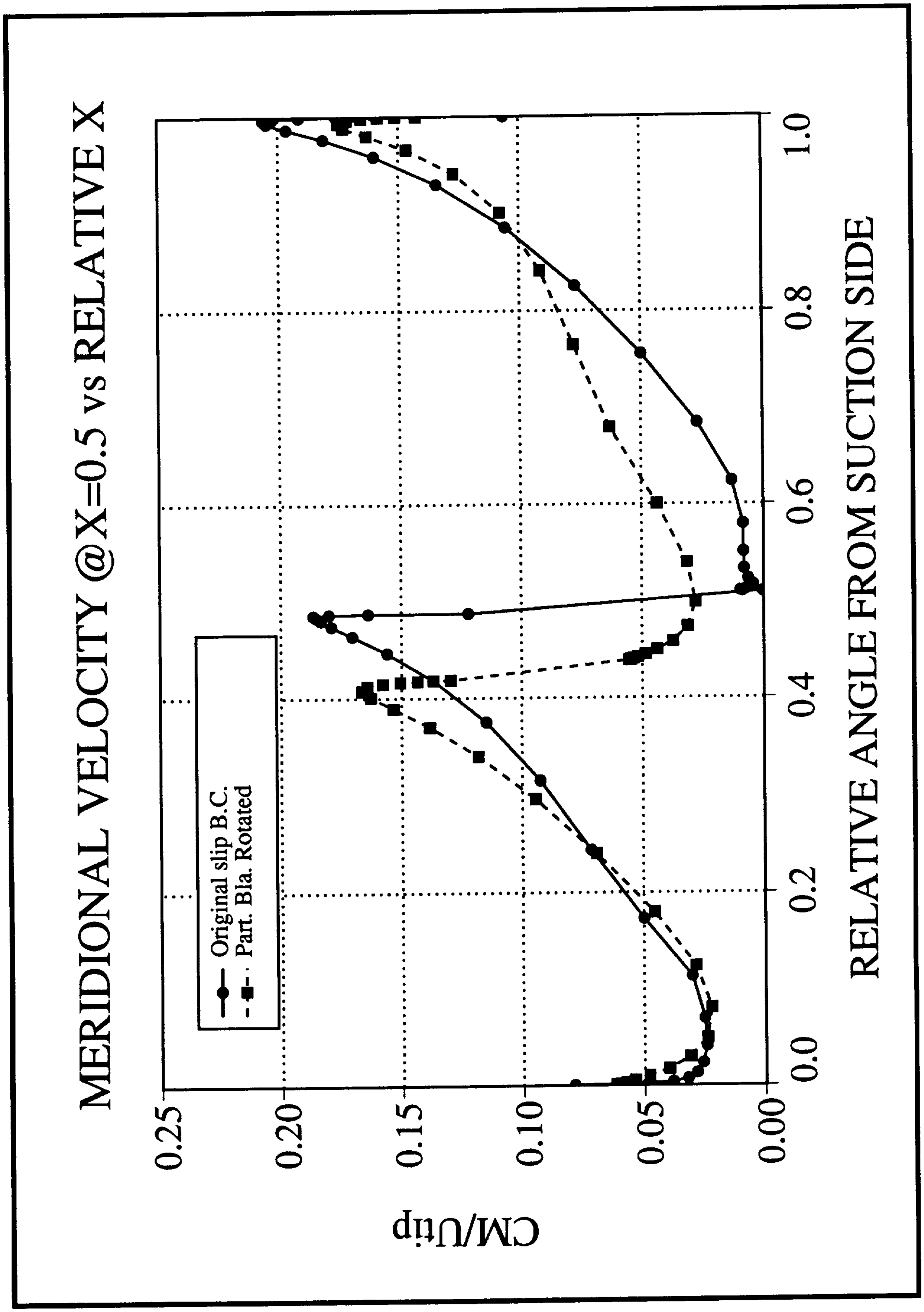
Advanced Impeller Computations

- Grid 1 : 111 x 25 x 33
- Grid 2 : 111 x 25 x 33
- Grid 3 : 61 x 72 x 33 / slip b.c. total : 328 K
- Grid 4 : 45 x 72 x 33
- Grid 5 : 45 x 72 x 33 / + exit cavities total : 542 K
- Grid 6 : 52 x 72 x 15 / + shroud cavity total : 598 K

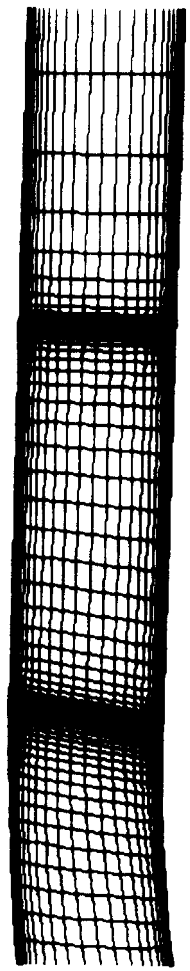
Flow Split

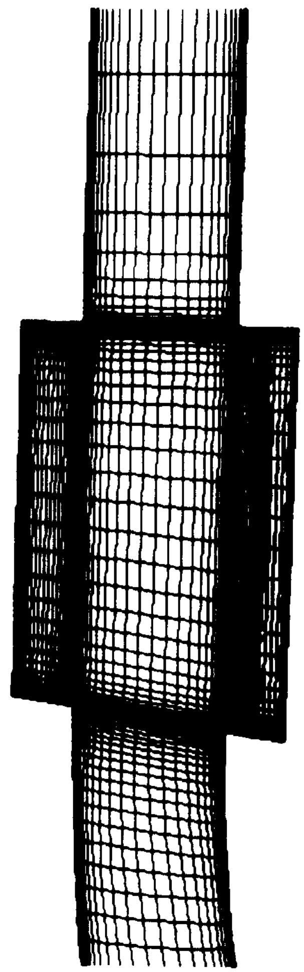
- Full Blade S.S. - Short Blade P.S. : % 48.7 (comp) % 49.0 (exp)
- Short Blade S.S. - Full Blade P.S. : % 51.3 (comp) % 51.0 (exp)

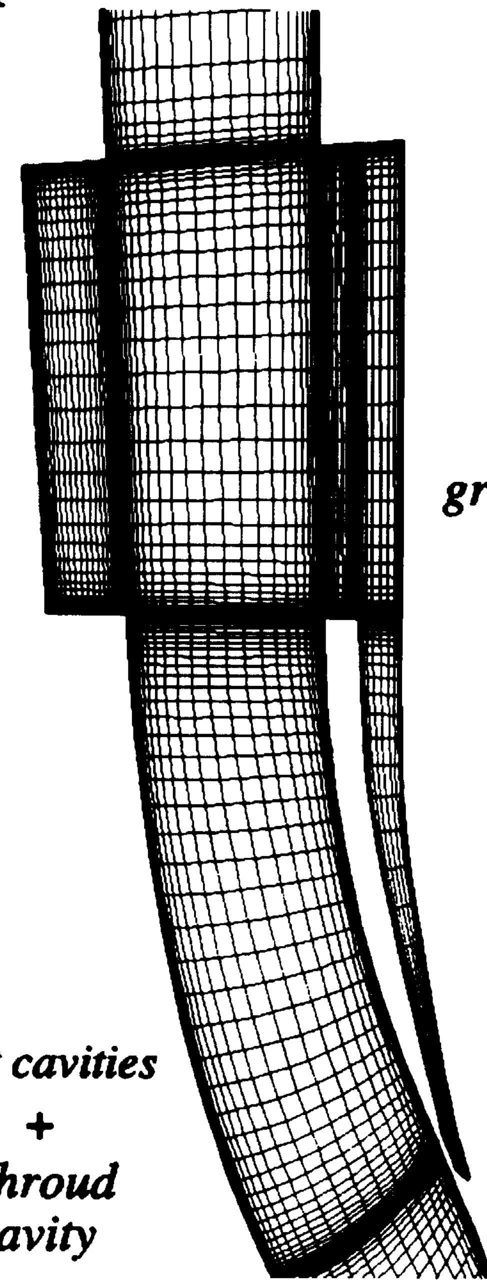

EFFICIENCY vs RELATIVE X
Original slip B.C.
Part. Bl. Rotated
EFFICIENCY
1.02
1.00
0.98
0.96
0.94
0.92
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE X FROM SHROUD


MERIDIONAL VELOCITY @X=0.5 vs RELATIVE X
CM/Utip
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE ANGLE FROM SUCTION SIDE
Original slip B.C.
Part. Bla. Rotated

Advanced Impeller Concept

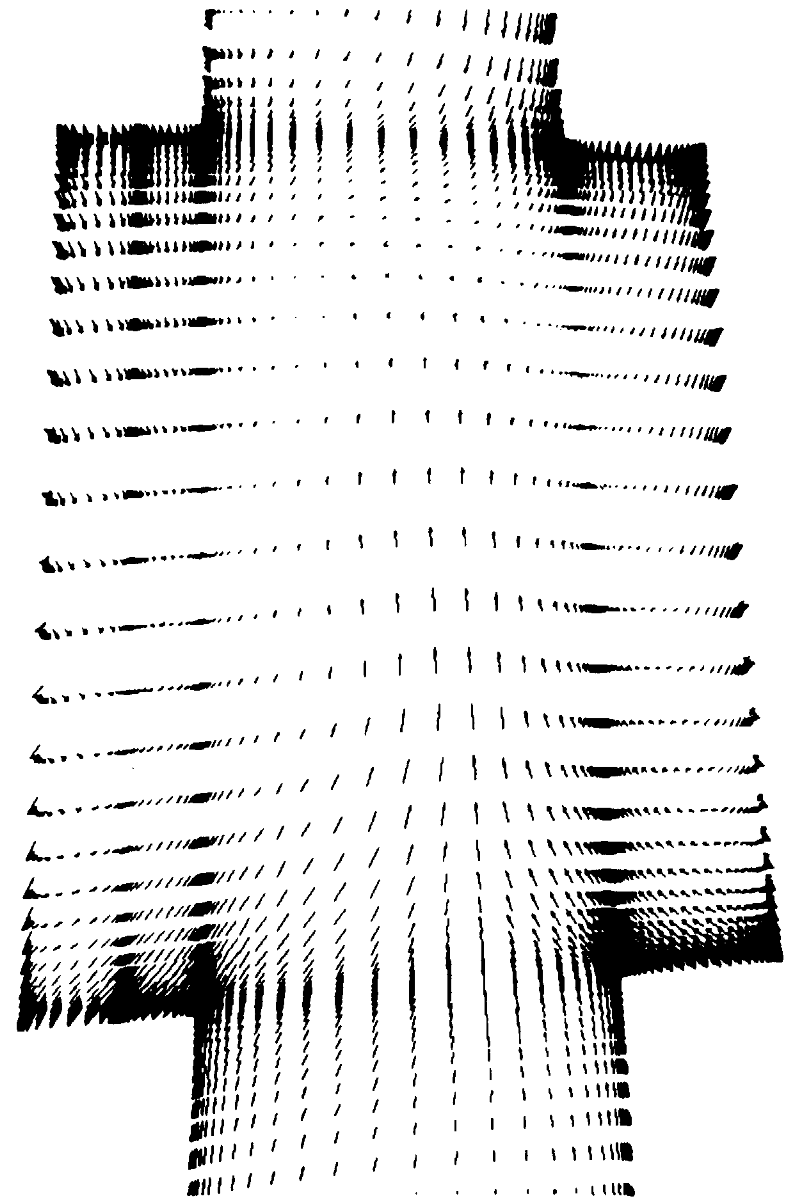






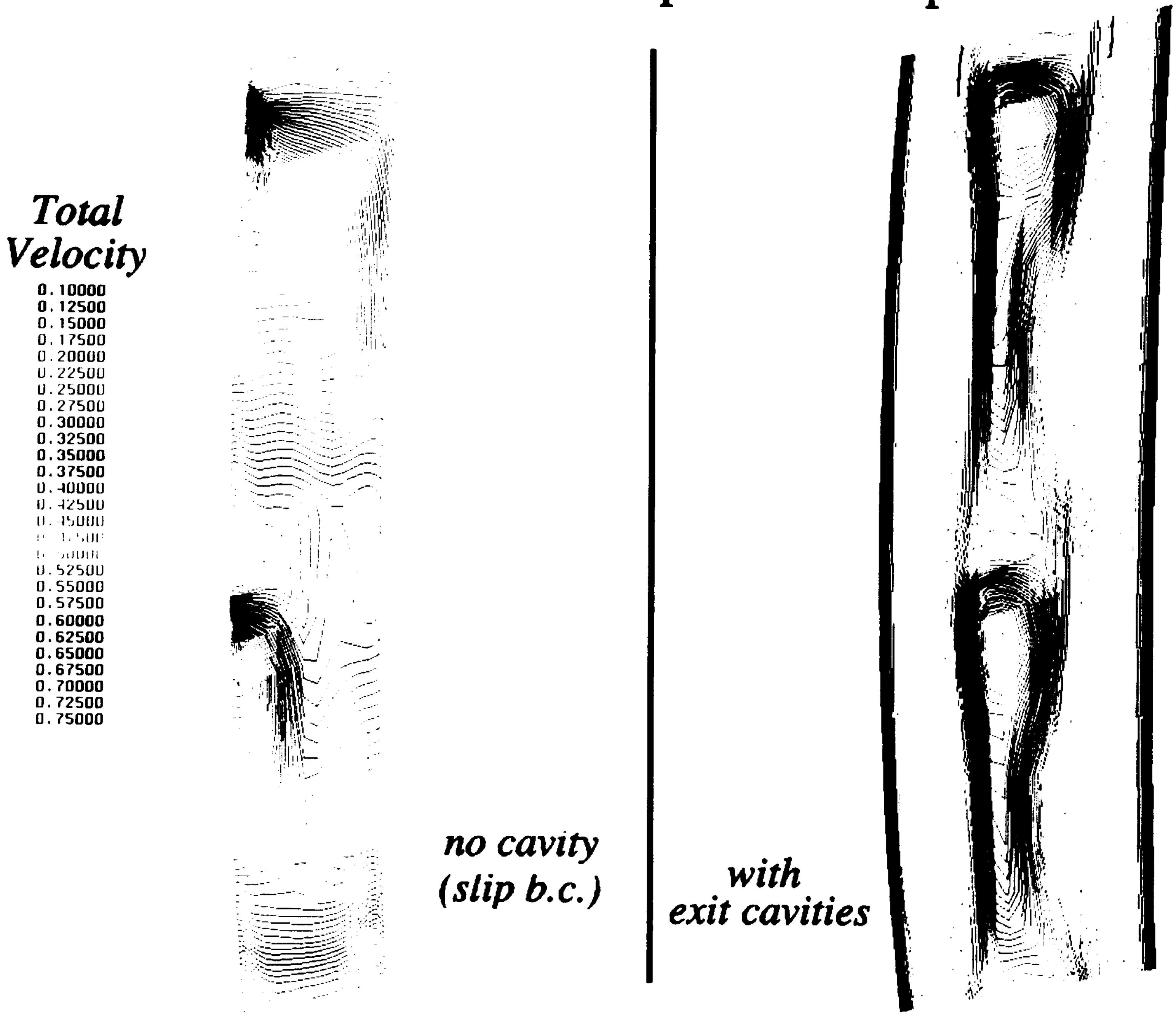
Advanced Impeller Concept

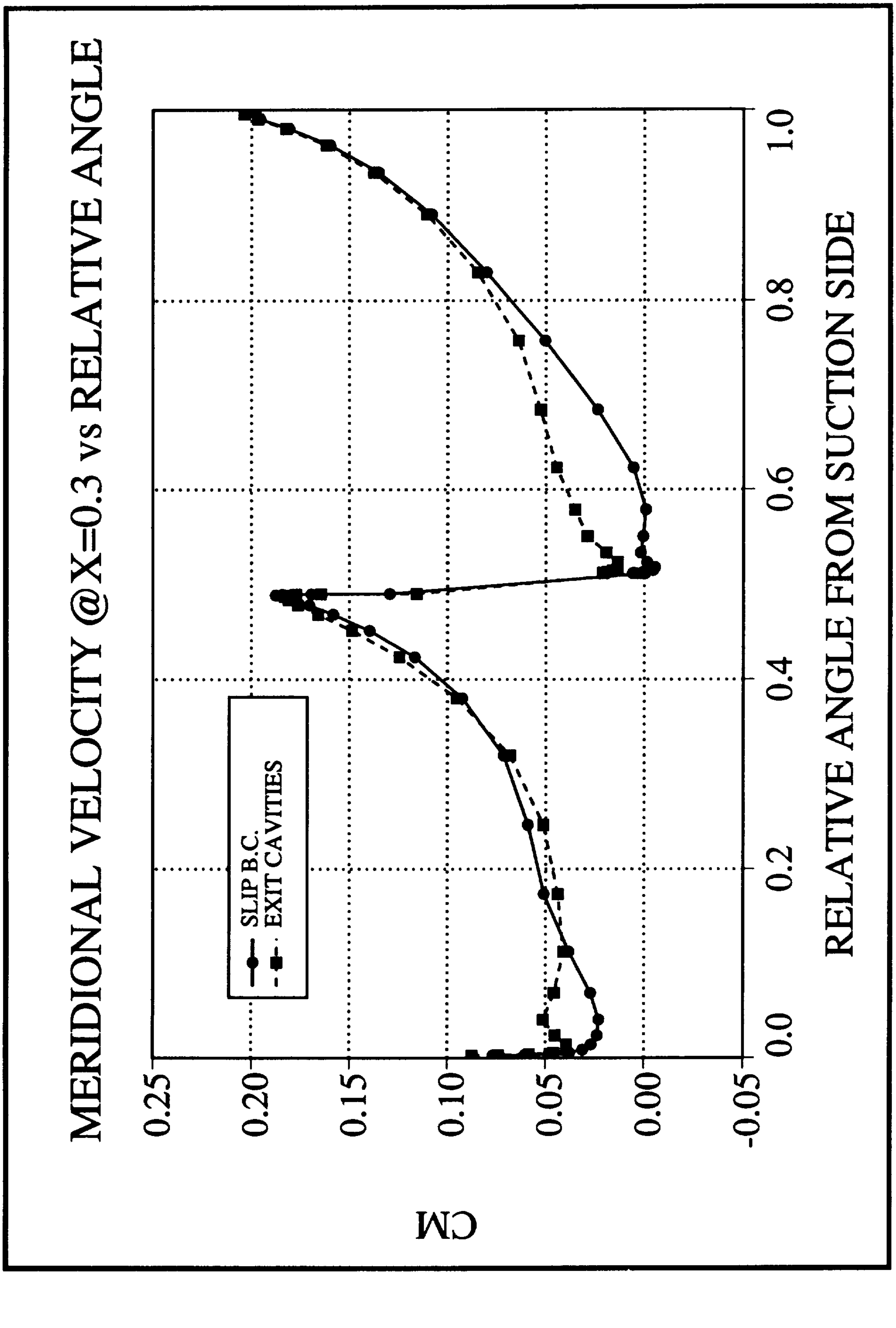
no cavity (slip b.c.)

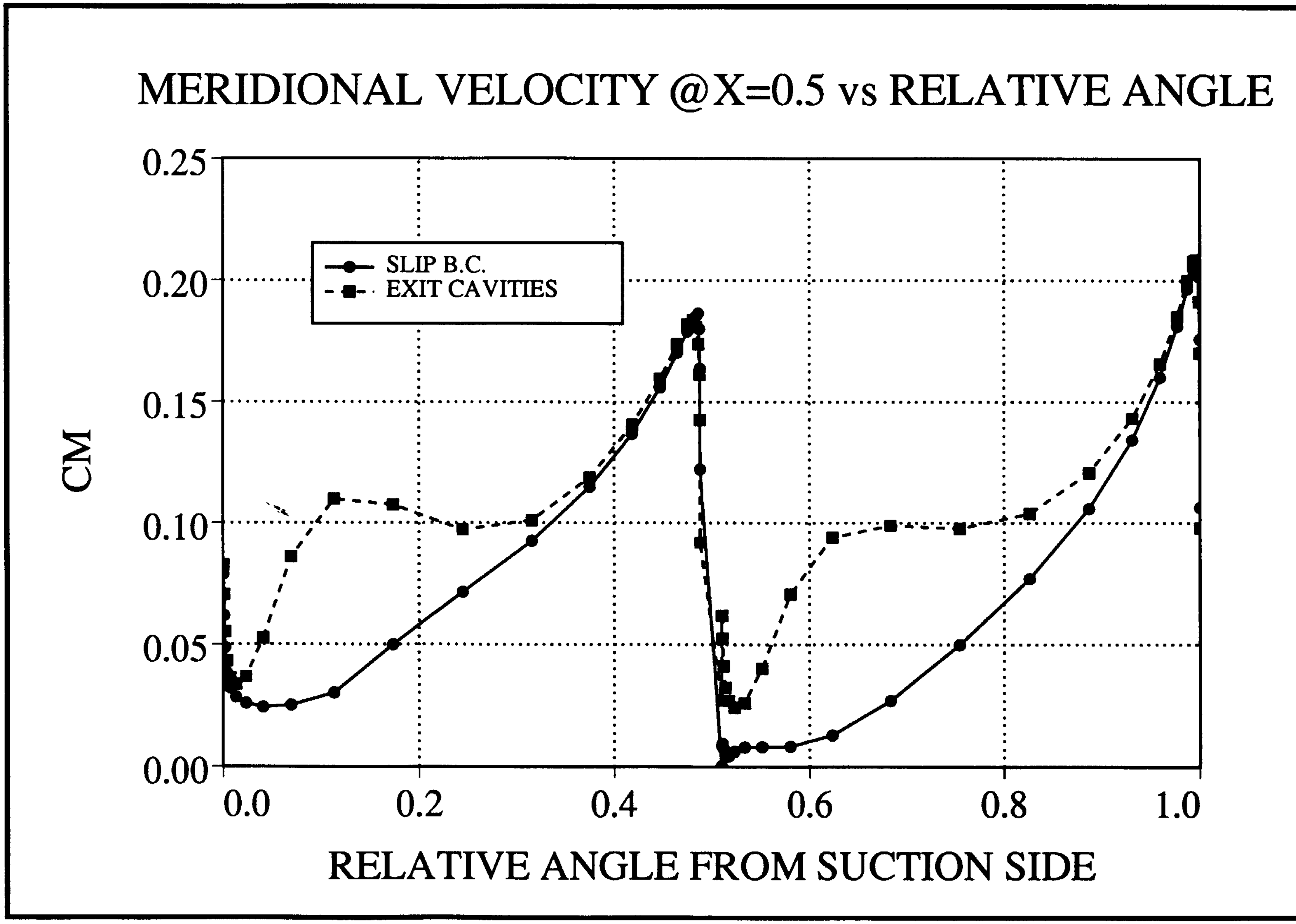


with exit cavities

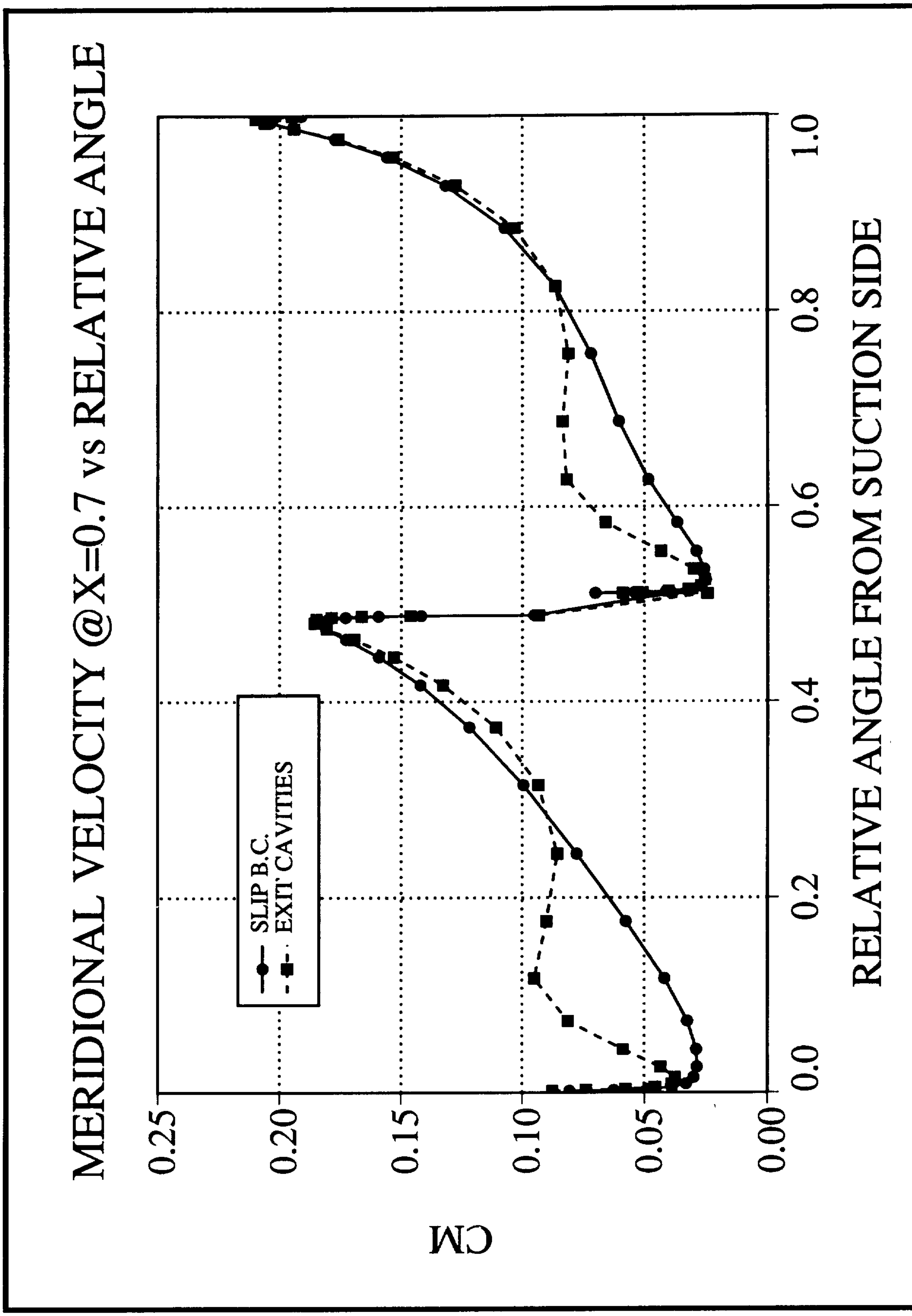
Advanced Impeller Concept



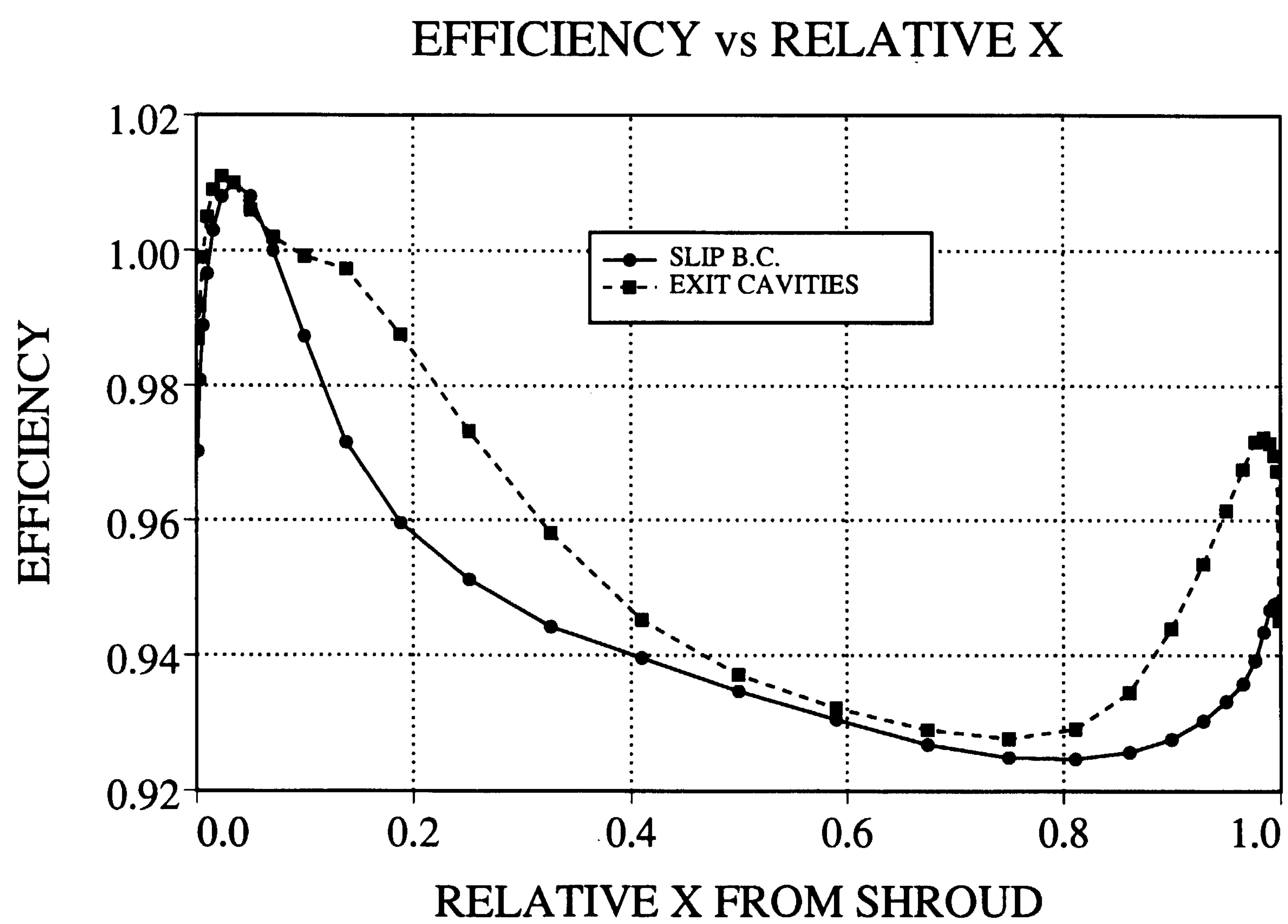

MERIDIONAL VELOCITY @X=0.3 vs RELATIVE ANGLE
CM
RELATIVE ANGLE FROM SUCTION SIDE
SLIP B.C.
EXIT CAVITIES
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0.0
0.2
0.4
0.6
0.8
1.0



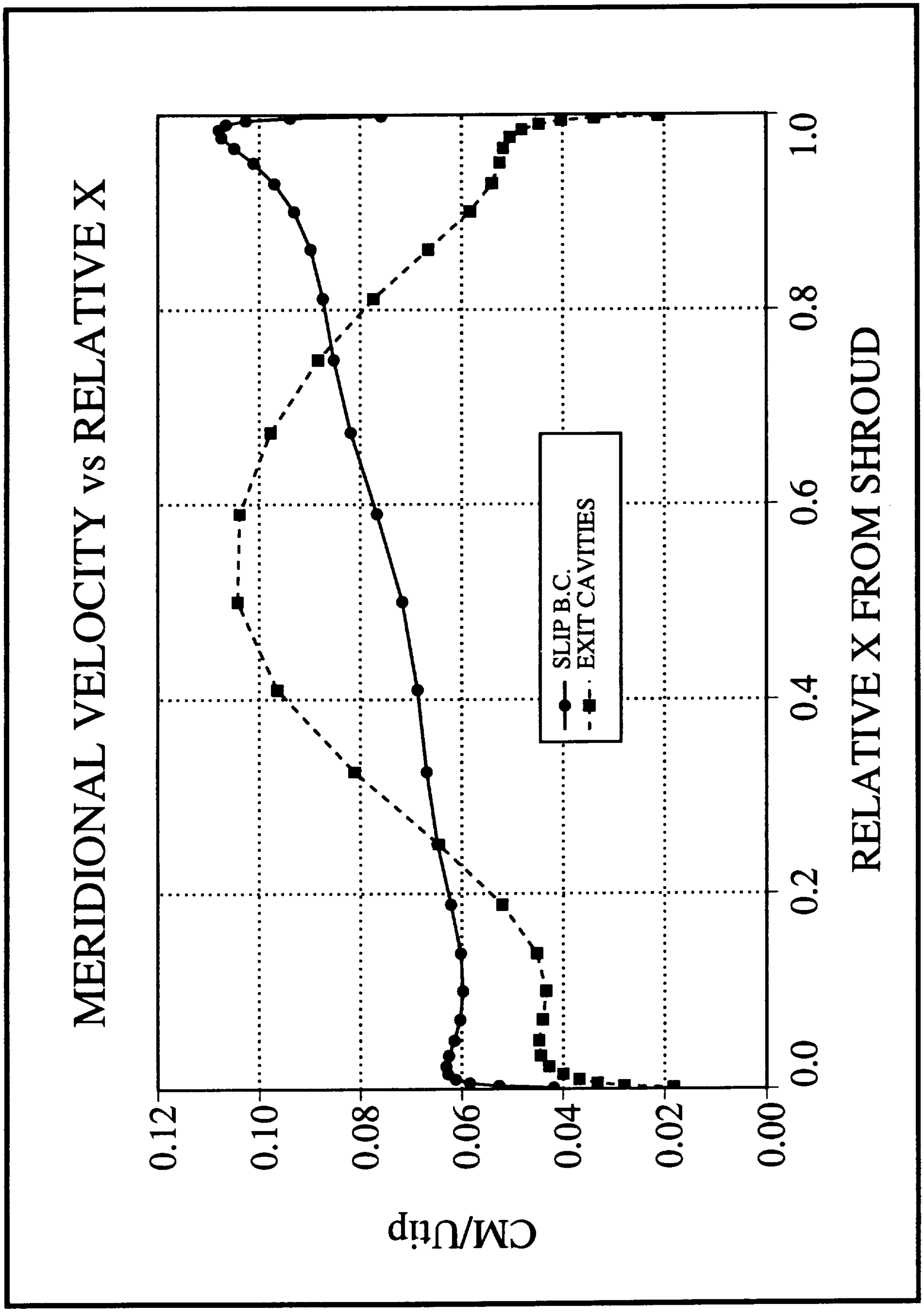
MERIDIONAL VELOCITY @X=0.5 vs RELATIVE ANGLE
CM
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE ANGLE FROM SUCTION SIDE
SLIP B.C.
EXIT CAVITIES

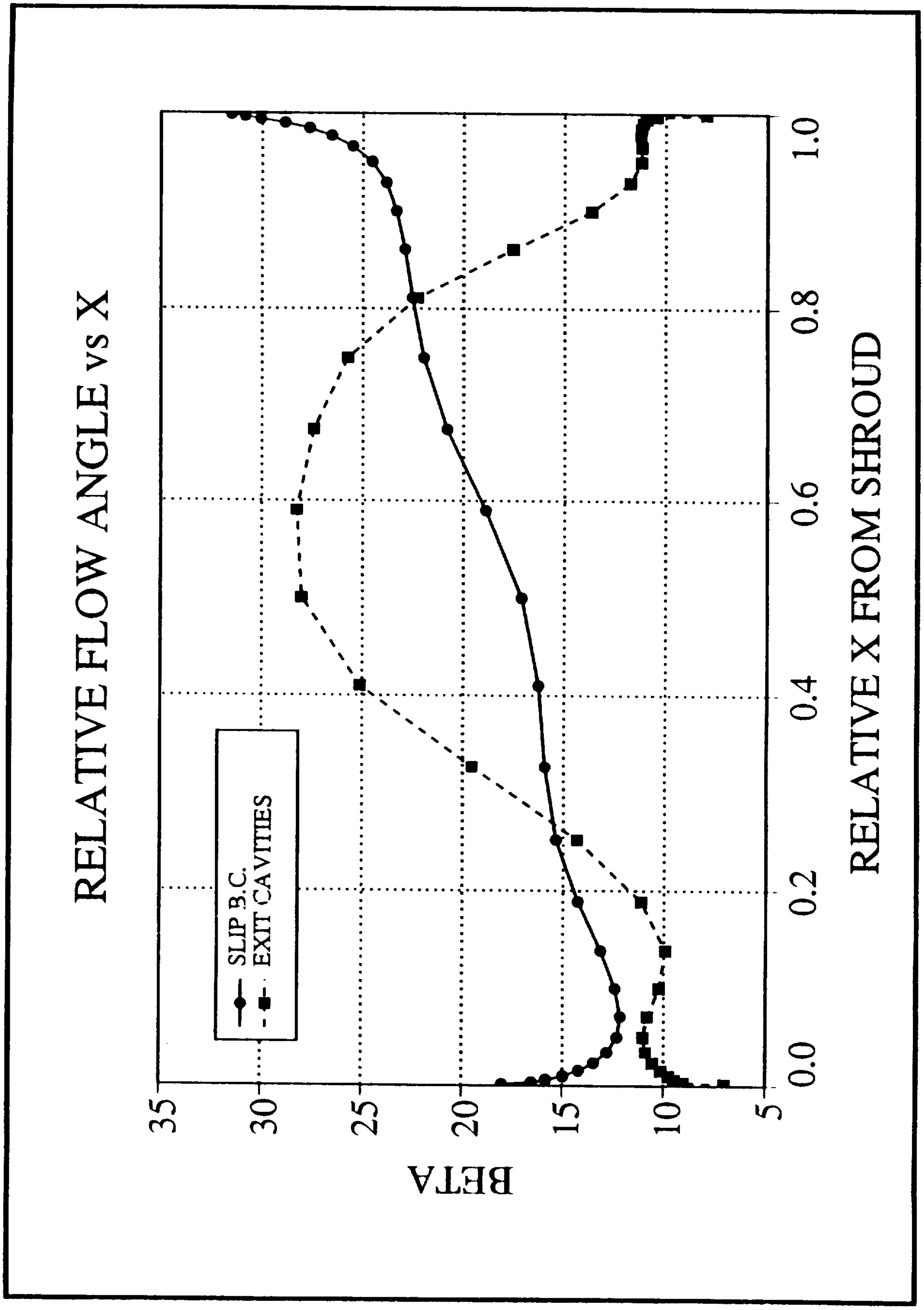


MERIDIONAL VELOCITY @X=0.7 vs RELATIVE ANGLE
CM
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE ANGLE FROM SUCTION SIDE
SLIP B.C.
EXIT CAVITIES

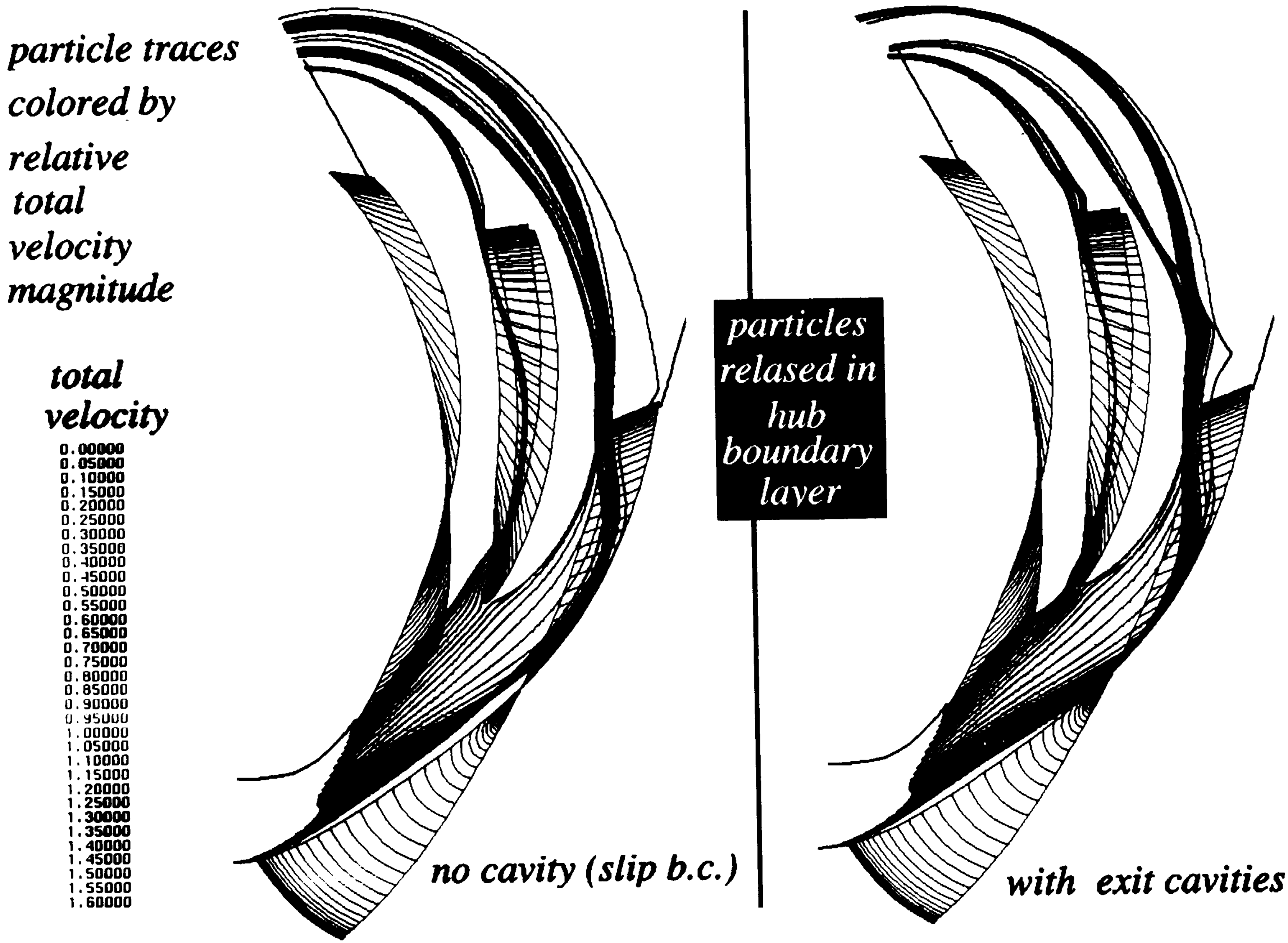


EFFICIENCY vs RELATIVE X
SLIP B.C.
EXIT CAVITIES
EFFICIENCY
1.02
1.00
0.98
0.96
0.94
0.92
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE X FROM SHROUD


MERIDIONAL VELOCITY vs RELATIVE X
CM/Utip
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE X FROM SHROUD
SLIP B.C.
EXIT CAVITIES


RELATIVE FLOW ANGLE vs X
SLIP B.C.
EXIT CAVITIES
BETA
35
30
25
20
15
10
5
0.0
0.2
0.4
0.6
0.8
1.0
RELATIVE X FROM SHROUD

Advanced Impeller Concept



Advanced Impeller Concept

particle traces colored by relative total velocity magnitude

total velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000
0.70000
0.75000
0.80000
0.85000
0.90000
0.95000
1.00000
1.05000
1.10000
1.15000
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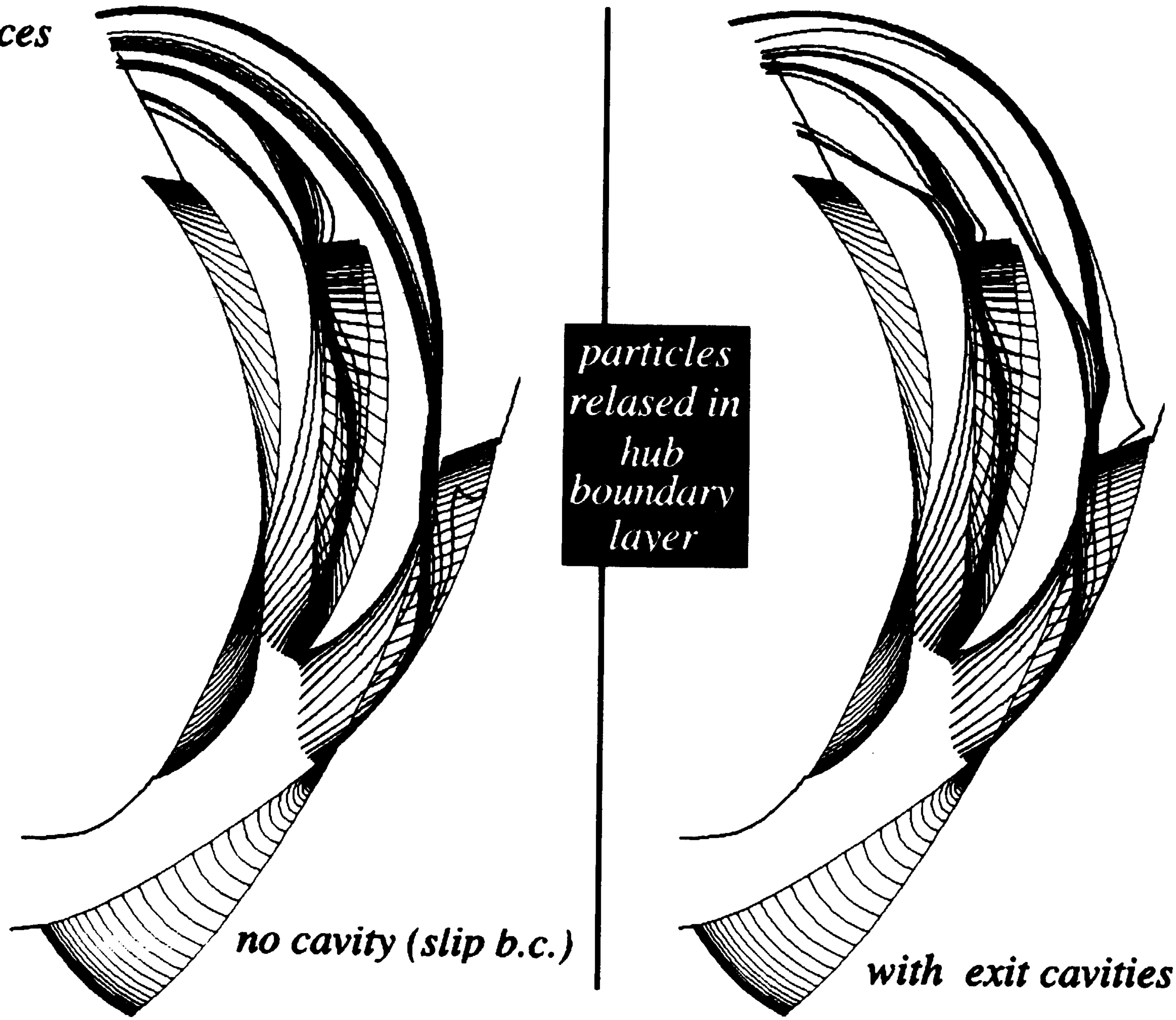
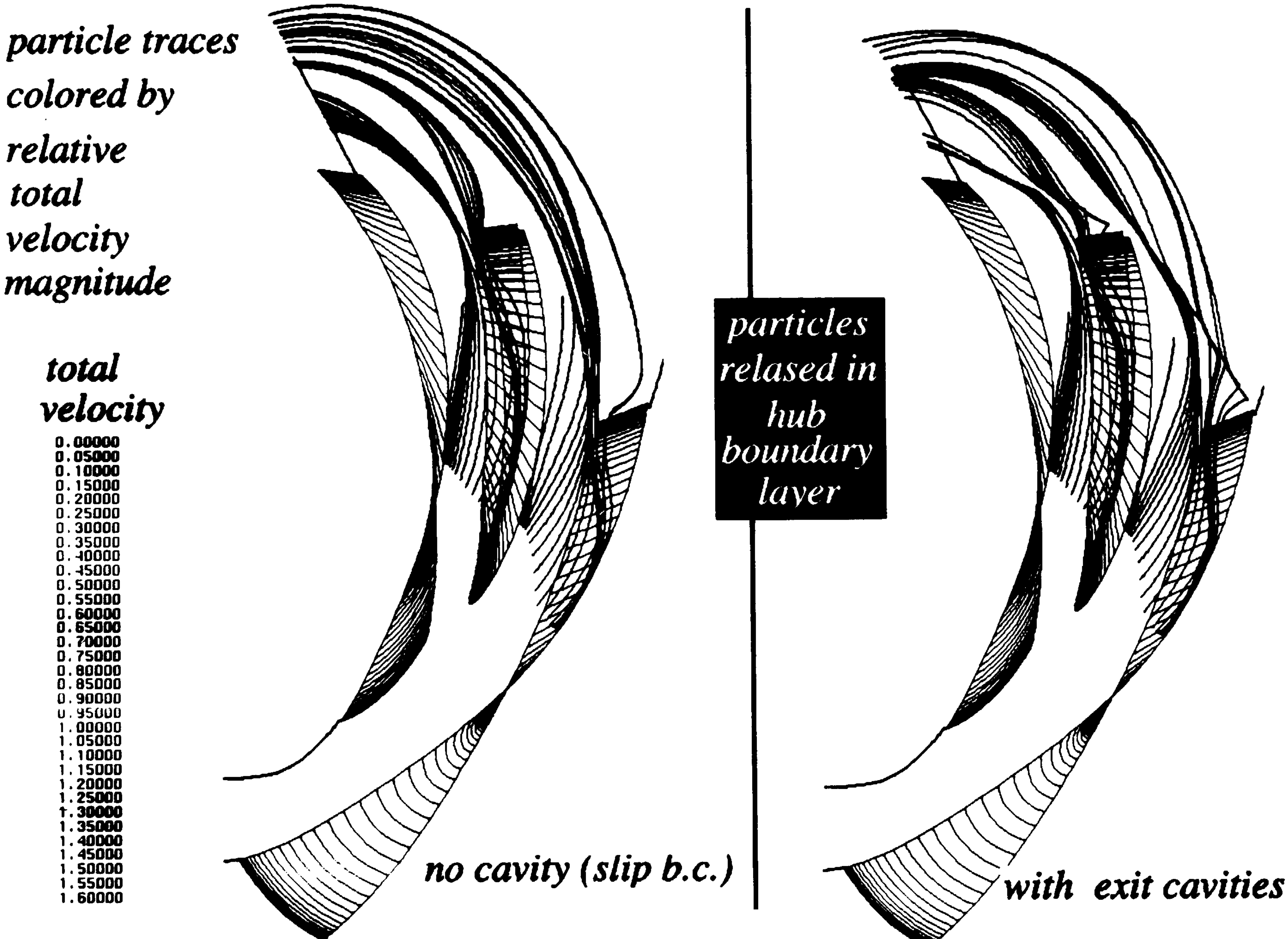
1.50000
1.55000
1.60000



Advanced Impeller Concept



Advanced Impeller Concept

particle traces colored by relative total velocity magnitude

total velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
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0.35000
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0.90000
0.95000
1.00000
1.05000
1.10000
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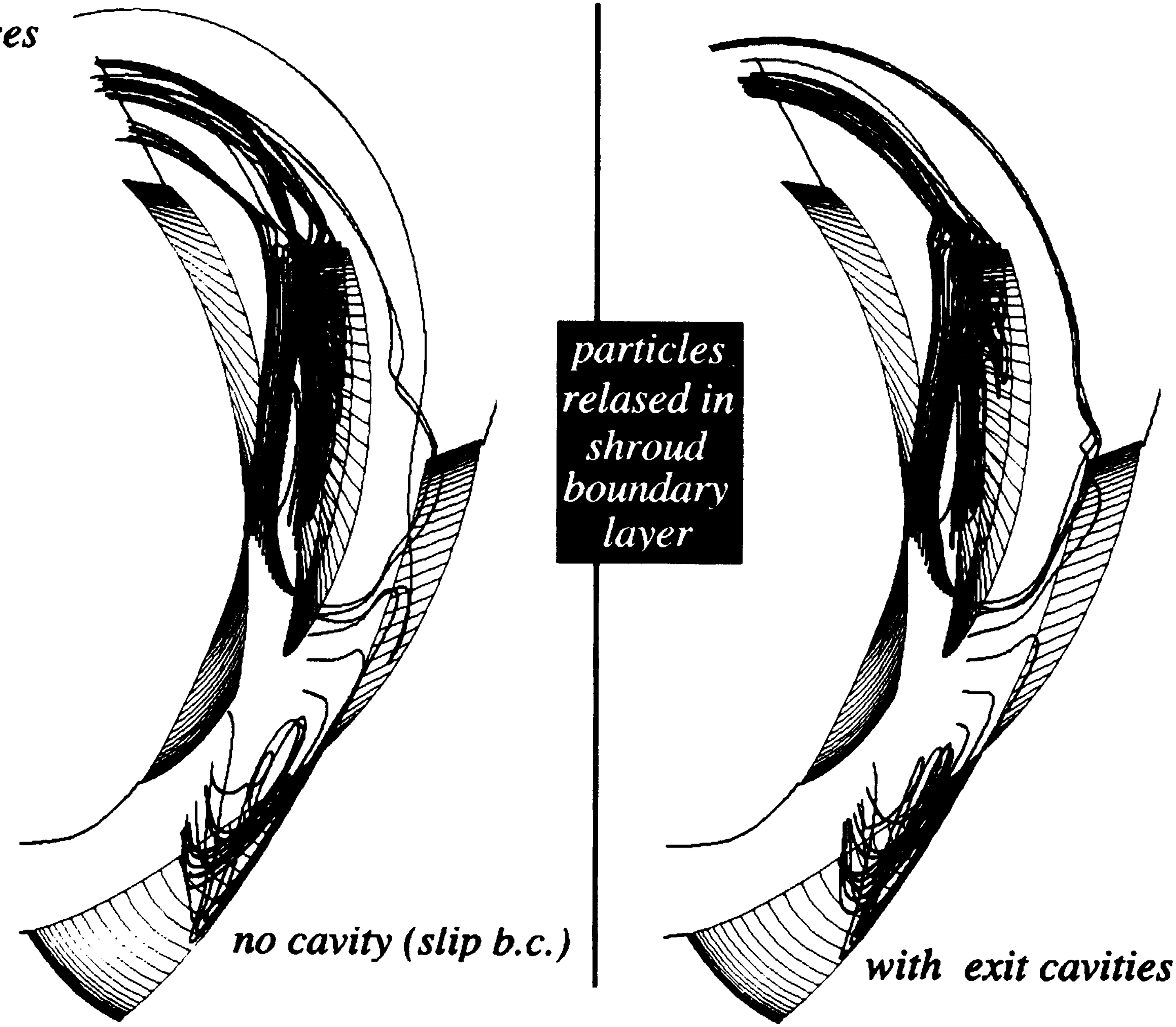
1.55000
1.60000



Advanced Impeller Concept

particle traces colored by relative total velocity magnitude

total velocity

0.00000
0.05000
0.10000
0.15000
0.20000
0.25000
0.30000
0.35000
0.40000
0.45000
0.50000
0.55000
0.60000
0.65000
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0.75000
0.80000
0.85000
0.90000
0.95000
1.00000
1.05000
1.10000
1.15000
1.20000
1.25000
1.30000
1.35000
1.40000
1.45000
1.50000
1.55000
1.60000

no cavity (slip b.c.)

particles relased in shroud boundary layer

with exit cavities

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Summary

- Solution procedure for rocket engine pump analysis was validated using benchmark problems.
- Preliminary comparison of 11 inch SSME-HPFTP impeller results show good agreement with the available experimental data.
- Advanced impeller design was analyzed with the conditions obtained from experiments The effect of exit cavities was shown at the impeller exit plane.
- Future work will focus on impeller-diffuser interaction and unsteady rotor-stator interaction.